Entry of the above amendments is earnestly solicited. An early and favorable first action on the merits is earnestly requested.

Should there be any matters that need to be resolved in the present application, the Examiner is respectfully requested to contact the undersigned at the telephone number listed below.

Attached hereto is a marked-up version of the changes made to the claims by the current amendment. The attached page is captioned "VERSION WITH MARKINGS TO SHOW CHANGES MADE."

The Commissioner is hereby authorized in this, concurrent, and future replies, to charge payment or credit any overpayment to Deposit Account No. 25-0120 for any additional fees required under 37 C.F.R. § 1.16 or under 37 C.F.R. § 1.17.

Respectfully submitted,

YOUNG & THOMPSON

Benoit Castel

Benoit Castel, Reg. No. 35,041

745 South 23rd Street
Arlington, VA 22202
Telephone (703) 521-2297

BC/lmt
Attachments

VERSION WITH MARKINGS TO SHOW CHANGES MADE

IN THE CLAIMS:

The claims have been amended as follows:

--3. (amended) Device according to claim 1~~ or 2~~, **characterised in that** the respective second refractive means (2_k) of the k element pairs (55_k) are positioned adjacent to each other, forming a second group, the respective second refractive means (2_k) in the second group being in physical contact.--

--4. (amended) Device according to claim 2~~ or 3~~, **characterised in that** the respective first and second refractive means (2_k, 4_k) of the k element pairs (55_k) are positioned symmetrically on respective sides of the first element pair (55_0).--

--5. (amended) Device according to ~~one of the claims 1 through 4,~~claim 1, **characterised in that** the refractive index (n_k) of the first refractive means (2_k) and the second refractive means (4_k) of a specific pair of the k element pairs (55_k) is substantially equal.--

--6. (amended) Device according to ~~one of the claims 1 through 5,~~claim 1, **characterised in that** spaces between the first refractive means (2_k) and the second refractive means (4_k) of each of the k element pairs (55_k) are filled with a predetermined medium having a predetermined refractive index (n_0).--

--7. (amended) Device according to ~~one of the claims 1 through 6,~~claim 1, **characterised in that** the device further comprises first control means for moving the first refractive means (2_k) and the second refractive means (4_k) of at least one of the k element pairs (55_k) with respect to each other, the direction of movement being perpendicular to a line of intersection of the input surface and output surface of the first refractive means (2_k).--

--8. (amended) Device according to ~~one of the claims 1 through 7,~~claim 1, **characterised in that** the first and second refractive means (2_k, 4_k) are formed by a first and a second prism (2, 4; 3, 5), respectively.--

--9. (amended) Device according to ~~one of the claims 1 through 8,~~claim 1, **characterised in that** the device (1) further comprises additional means (35, 36) of a dispersive material for applying a chromatic correction to the optical beam, in which the dispersive material has a refractive index which is different from the refractive index (n_k) of the first and second refractive means (2_k, 4_k) of the first pair (55_0) and plurality of further pairs (55_k).--

--11. (amended) Interferometer having a first input plane and a second input plane for receiving at least a first and a second optical beam and an interference plane for letting the at least first and second optical beam interfere, a first optical path being formed from the first input plane to the interference

plane and a second optical path being formed from the second input plane to the interference plane,

comprising optical path delay means for introducing an optical path difference between the first optical path and the second optical path, **characterised in that** the interferometer further comprises at least one achromatic phase shift device according to ~~one of the claims 1 through 10,~~claim 1, positioned in at least one of the first optical path and the second optical path.--

--13. (amended) Interferometer according to claim 11~~ or 12~~, **characterised in that** the interferometer comprises main control means for maintaining the phase shift (Ψ_0) between the at least first and second beam at a predetermined value, the main control means being connected to the optical path delay means (26, 27), and the first control means.--

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Achromatic phase shift device and interferometer using achromatic phase shift device

The present invention relates to an achromatic phase shift device for introducing a wavelength independent optical phase shift in a first optical beam during operation, ~~comprising at least one dispersive element~~according to the preamble of claim 1. A second aspect of the present invention relates to an interferometer using such an achromatic phase shift device.

The American patent US-A-5,862,001 describes a non-deviating prism with a continuously variable dispersion. This arrangement of optical elements allows to obtain a variable angular dispersion without any angular deviation at a central wavelength.

The most common means for obtaining a phase shift in an optical beam are phase shift devices using optical path delay means to influence the optical path of the beam and, thus, the phase of the optical beam. A disadvantage of such a known phase shift device is that the phase shift obtained is dependent on the wavelength. For applications in which the bandwidth of the light beam used is very small, this is not necessarily a problem. However, when a phase shift is needed in an optical beam with a broader bandwidth, the known device does not suffice.

This may for instance be the case for the application of an achromatic phase shift device in an interferometer, used in observation of planets near stars. These interferometers are for instance used in optical synthetic aperture systems, using multiple optical beams from different telescopes separated by a certain baseline. The optical beams from the telescopes usually have a broad wavelength. To be able to detect planets near stars, the light of the star is nulled in the interferometer by introducing a phase difference of π radians between the interfering beams. Using known phase shift devices, a suppression factor of 100 may be obtained, while for certain detections a suppression factor of 10^6 is necessary.

In the prior art, achromatic phase shift in an optical beam is accomplished using an achromatic phase shift device, which comprises dispersive elements being formed by at least two plan parallel plates with a different refractive index. The dispersive elements effectuate a wavelength dependent optical path difference, and with the right combination of materials (refractive index) and dimensions of the plates, an achromatic phase shift can be accomplished over a certain wavelength range. However, the dimensions of the plates are fixed and, therefore, the phase shift accomplished is fixed.

amended page 2

Also, at least two materials are needed with a different refractive index, which may be disadvantageous in numerous applications.

It is an object of the present invention to provide a phase shift device for producing a phase shift over a wide frequency range, i.e. an achromatic phase shift device. It is a secondary object of the present invention to provide an interferometer, which is particularly suited for planet detection near distant stars, by nulling the light from the associated star.

The first object is achieved by a phase shift device according to the preamble of claim 1, having the characteristic features of the characterising part of claim 1.~~characterised in that the at least one dispersive element comprises a first pair formed by first refractive means and second refractive means, the first refractive means having a first refractive means input plane for receiving the first optical beam and a first refractive means output plane, the first refractive means input plane and the first refractive means output plane being at a predetermined angle β to each other, 0 < β < π/2, the second refractive means having a second refractive means input plane and a second refractive means output plane, said second refractive means input plane being positioned equidistant to the first refractive means output plane and the second refractive means output plane being positioned parallel to the first refractive means input plane.~~

not permitted

The arrangement of the device allows introducing a phase shift in an optical beam travelling through the device, by varying the position of the first refractive means relative to the second refractive means. The first and second refractive means may be placed at a certain distance to one another and have small dimensions, which are sufficient for refracting the optical beam in the device as desired.

~~In a further embodiment of the present invention, the device further comprises a plurality of k further pairs, k being an integer between 1 and M, each further pair comprising respective first refractive means and respective second refractive means, the respective first refractive means of each of the plurality of further pairs having a first refractive means input plane for receiving the first optical beam and a first refractive means output plane, the first refractive means input plane and the first refractive means output plane being at a predetermined angle β~~~~$_k$~~ ~~to each other, 0 < β~~~~$_k$~~ ~~< π/2, the respective second refractive means of each of the plurality of further pairs having a second refractive means input plane and a second refractive means output plane, said~~

amended page 3

~~second refractive means input plane being positioned equidistant to the first refractive means output plane and the second refractive means output plane being positioned parallel to the first refractive means input plane.~~

Using multiple ~~the further~~ pairs of respective first and second refractive means, it becomes possible to obtain a phase shift of an optical beam through the achromatic phase shift device, which is wavelength independent over a broad wavelength region.

In this embodiment, a perfect match of the predetermined phase shift is obtained for M+1 wavelengths.

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In an embodiment of the achromatic phase shift device according to the present invention, the respective first refractive means of the plurality of further pairs are positioned adjacent to each other, forming a first group, the respective first refractive means in the first group being in physical contact. Preferably, also the respective second refractive means of the plurality of further pairs are positioned adjacent to each other, forming a second group, the respective second refractive means in the second group being in physical contact. By positioning the respective first and second refractive means such that they are in physical contact, interfaces occur between materials of different refractive index. The feature that the elements are in physical contact enables producing achromatic phase shift devices in a reliable and robust manner.

In a preferred embodiment of the achromatic phase shift device according to the present invention, the respective first and second refractive means of the plurality of further pairs are positioned symmetrically on respective sides of the first element pair. This allows a very compact arrangement of the device according to the present invention.

In a further embodiment, the refractive index ~~all~~ of the first refractive means and the second refractive means of a specific pair of the element pairs ~~all of first pair and the plurality of further pairs have a~~is substantially equal~~ refractive index~~. This has advantages with respect to production of the device (only one dispersive material is needed), but also during operation, as environmental conditions will have less impact when all refractive means are made of the same material.

In certain arrangements of the first and second refractive means of the phase shift device, spaces may exist between the first refractive means and the second refractive means of each of the first pair and the plurality of further pairs. Preferably, these spaces

are filled with a predetermined medium having a predetermined refractive index. The medium can be air, a liquid or vacuum. For further calculating purposes, these spaces can also be regarded as forming first and second refractive means.

To be able to use the device as a phase modulator, the device further comprises first control means for moving the first refractive means and the second refractive means of each of the first pair and the plurality of further pairs with respect to each other. Preferably, the direction of movement is perpendicular to a line of intersection of the input surface and output surface of the first refractive means. This allows variation of the distance travelled by the optical beam through the first and second refractive means and between the first and second refractive means of one or more of the first pair and the plurality of further pairs. This may be achieved very accurately by various control means known to the person skilled in the art.

It will be clear to the person skilled in the art that the change in position of the first refractive means relative to the second refractive means may be obtained by moving the first refractive means, the second refractive means, or both.

In an embodiment, the first and second refractive means are preferably formed by a first and a second prism, respectively. Such prisms with the required dimensions can be readily obtained or are easy to manufacture.

In a further embodiment, the device further comprises additional means of a dispersive material for applying a further chromatic correction to the optical beam, in which the dispersive material has a refractive index, which is different from the refractive index of the first and second refractive means. This embodiment enables a further achromatic correction, diminishing the higher order wavelength dependent errors in the chromatic correction.

~~In a preferred embodiment, the device introduces a predetermined phase shift ψ_0 between the first optical beam and a second optical beam, the second optical beam running substantially parallel to the first optical beam over an optical path length w_0, a first optical axis being defined from a device input surface to a device output surface, the first refractive means having a first distance d_k' along the first optical axis and the second refractive means having a second distance d_k'' along the first optical axis, the first optical beam being at an angle θ_k with the first optical axis and a modified refractive index being defined as $a_k = n_k \cos \theta_k$, in which the sum d_k of the first and second distance of the first and second refractive means and the required optical path~~

amended page 5

~~w_0 are determined by solving the following equations for the wavelengths at which the predetermined phase shift should be obtained exactly:~~

$$-w_0 + a_0(\lambda_0)\,d_0 + \cdots\cdots + a_{M-1}(\lambda_0)\,d_{M-1} = \frac{\psi_0}{2\pi}\lambda_0$$

$$\vdots \qquad\qquad \vdots \qquad\qquad \vdots$$

$$-w_0 + a_0(\lambda_M)\,d_0 + \cdots\cdots + a_{M-1}(\lambda_M)\,d_{M-1} = \frac{\psi_0}{2\pi}\lambda_M$$

)?

~~In this embodiment, a perfect match of the predetermined phase shift is obtained for M+1 wavelengths.~~

In an alternative embodiment the sum of the first and second distance of the first and second refractive means and the required optical path are determined by requiring constant terms and terms with λ^2, λ^3... λ^M to become zero and the term with λ to become equal to $\psi_0/2\pi$ in the equation for the introduced optical path length difference $w_d(\lambda)$ according to

$$w_d(\lambda) = -w_0 + \sum_{k=0}^{M-1}\{a_{k0} + a_{k1}(\lambda-\lambda_0) + a_{k2}(\lambda-\lambda_0)^2 \cdots\cdots\}\,d_k$$

in which a_{k0}, a_{k2}, ... = series expansion coefficients of the modified refractive index a_k, according to $a_k = a_{k0} + a_{k1}(\lambda-\lambda_0) + a_{k2}(\lambda-\lambda_0)^2 \cdots\cdots$, and in which λ is a wavelength of the optical beam and λ_0 is a central wavelength of a predetermined spectral band.

In this alternative embodiment, an M-th order fit is obtained for the wavelength dependent phase shift around the central wavelength λ_0.

By changing the design parameters of the first and second refractive means, the phase shift obtained is independent of the wavelength of the optical beam. This allows introducing a constant, wavelength independent phase shift in optical beams having a relatively broad bandwidth.

With the achromatic phase shift device according to the present invention, applications can be made for adjustment, modulation and/or closed loop control of the phase difference of broad band, interfering optical beams.

A second aspect of the present invention relates to an interferometer having a first input plane and a second input plane for receiving at least a first and a second optical beam and an interference plane for letting the at least first and second optical beam interfere, a first optical path being formed from the first input plane to the interference

amended page 5a

plane and a second optical path being formed from the second input plane to the interference plane, comprising optical path delay means for introducing an optical path difference between the first optical path and the second optical path, characterised in that the interferometer further comprises at least one achromatic phase shift device according to the invention, positioned in at least one of the first optical path and the second optical path.

CLAIMS

1. Achromatic phase shift device for introducing a wavelength independent optical phase shift in a first optical beam during operation, comprising at least one dispersive element,

~~characterised in that~~

the at least one dispersive element comprisinges ~~a first~~ k element pairs (55_{k0}), k being an integer between 1 and M, each element pair being formed by respective first refractive means (2_k) and second refractive means (4_k),

the respective first refractive means (2_k) having a first refractive means input plane (6) for receiving the a first optical beam ~~(40) and a first refractive means output plane (8)~~, the first refractive means input plane (6) and the first refractive means output plane (8) being at a predetermined angle β_k to each other, $0 < \beta_k < \pi/2$,

the respective second refractive means (4_k) having a second refractive means input plane (10) and a second refractive means output plane (12), said second refractive means input plane (10) being positioned equidistant to the first refractive means output plane (8) and the second refractive means output plane (12) being positioned parallel to the first refractive means input plane (6).

~~2. Device according to claim 1, characterised in that the device further comprises a plurality of k further pairs (55_k), k being an integer between 1 and M, each further pair (55_k) comprising respective first refractive means (2_k) and respective second refractive means (4_k),~~

~~the respective first refractive means (2_k) of each of the plurality of further pairs (55_k) having a first refractive means input plane (6) for receiving the first optical beam (40) and a first refractive means output plane (8), the first refractive means input plane (6) and the first refractive means output plane (8) being at a predetermined angle β_k to each other, $0 < \beta_k < \pi/2$,~~

~~the respective second refractive means (4_k) of each of the plurality of further pairs (55_k) having a second refractive means input plane (10) and a second refractive means output plane (12), said second refractive means input plane (10) being positioned equidistant to the first refractive means output plane (8) and the second refractive means output plane (12) being positioned parallel to the first refractive means input plane (6).~~

A1

characterised in that

the device (1) introduces a predetermined phase shift ψ_0 between the first optical beam (40) and a second optical beam (41), the second optical beam (41) running substantially parallel to the first optical beam (40) over an optical path length w_0, a first optical axis (50) being defined from a device input surface (51) to a device output surface (52), the first refractive means (2_k) having a first distance d_k' along the first optical axis (50) and the second refractive means having a second distance d_k'' along the first optical axis (50), the first optical beam (40) being at an angle θ_k with the first optical axis (50) and a modified refractive index a_k being defined as $a_k = n_k \cos \theta_k$,

A1

in which the sum d_k of the first and second distance of the first and second refractive means (2_k, 4_k), respectively and the required optical path w_0 are determined by solving the following equations for the wavelengths ($\lambda_0 \ldots \lambda_M$) at which the predetermined phase shift ψ_0 should be obtained exactly:

$$
\begin{array}{l}
-w_0 + a_0(\lambda_0)\,d_0 + \cdots\cdots + a_{M-1}(\lambda_0)\,d_{M-1} = \dfrac{\psi_0}{2\pi}\lambda_0 \\
\vdots \qquad\qquad\qquad \vdots \qquad\qquad \vdots \\
-w_0 + a_0(\lambda_M)\,d_0 + \cdots\cdots + a_{M-1}(\lambda_M)\,d_{M-1} = \dfrac{\psi_0}{2\pi}\lambda_M
\end{array}
$$

2~~3~~. Device according to claim 1~~2~~, **characterised in that** the respective first refractive means (2_k) of the ~~plurality of further~~k element pairs (55_k) are positioned adjacent to each other, forming a first group, the respective first refractive means (2_k) in the first group being in physical contact.

Sub A2

3~~4~~. Device according to claim 1~~2~~ or 2~~3~~, **characterised in that** the respective second refractive means (2_k) of the ~~plurality of further~~ k element pairs (55_k) are positioned adjacent to each other, forming a second group, the respective second refractive means (2_k) in the second group being in physical contact.

4~~5~~. Device according to claim 2~~3~~ or 3~~4~~, **characterised in that** the respective first and second refractive means (2_k, 4_k) of the ~~plurality of further~~k element pairs (55_k) are positioned symmetrically on respective sides of the first element pair (55_0).

5~~6~~. Device according to one of the claims 1~~2~~ through ~~5~~4, **characterised in that** ~~all of~~ the refractive index (n_k) of the first refractive means (2_k) and the second refractive means (4_k) of a specific pair ~~all~~ of the ~~plurality of further~~k element pairs (55_k) is ~~have a~~ substantially equal ~~refractive index (n_k)~~.

Sub A2

6~~7~~. Device according to one of the claims 1 through 5~~6~~, **characterised in that** spaces between the first refractive means (2_k) and the second refractive means (4_k) of each of the ~~first pair (55_0) and plurality of further~~k element pairs (55_k) are filled with a predetermined medium having a predetermined refractive index (n_0).

A1

7~~8~~. Device according to one of the claims 1 through 6~~7~~, **characterised in that** the device further comprises first control means for moving the first refractive means (2_k) and the second refractive means (4_k) of at least one of the ~~first pair (55_0) and the plurality of further~~k element pairs (55_k) with respect to each other, the direction of movement being perpendicular to a line of intersection of the input surface and output surface of the first refractive means (2_k).

8~~9~~. Device according to one of the claims 1 through 7~~8~~, **characterised in that** the first and second refractive means (2_k, 4_k) are formed by a first and a second prism (2, 4; 3, 5), respectively.

9~~10~~. Device according to one of the claims 1 through 8~~9~~, **characterised in that** the device (1) further comprises additional means (35, 36) of a dispersive material for applying a chromatic correction to the optical beam, in which the dispersive material has a refractive index which is different from a refractive index (n_k) of the first and second refractive means (2_k, 4_k) of the first pair (55_0) and plurality of further pairs (55_k).

~~11. Device according to one of the claims 1 through 10, **characterised in that** the device (1) introduces a predetermined phase shift ψ_0 between the first optical beam (40) and a second optical beam (41), the second optical beam (41) running substantially parallel to the first optical beam (40) over an optical path length w_0, a first optical axis (50) being defined from a device input surface (51) to a device output surface (52), the~~

~~first refractive means (2_k) having a first distance d_k' along the first optical axis (50) and the second refractive means having a second distance d_k'' along the first optical axis (50), the first optical beam (40) being at an angle θ_k with the first optical axis (50) and a modified refractive index a_k being defined as $a_k = n_k \cos \theta_k$,~~

~~in which the sum d_k of the first and second distance of the first and second refractive means (2_k, 4_k), respectively and the required optical path w_0 are determined by solving the following equations for the wavelengths ($\lambda_0 \ldots \lambda_M$) at which the predetermined phase shift ψ_0 should be obtained exactly:~~

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A1

$$\cancel{\begin{array}{c} -w_0 + a_0(\lambda_0)\,d_0 + \cdots\cdots + a_{M-1}(\lambda_0)\,d_{M-1} = \dfrac{\psi_0}{2\pi}\lambda_0 \\ \vdots \qquad\qquad \vdots \qquad\qquad \vdots \\ -w_0 + a_0(\lambda_M)\,d_0 + \cdots\cdots + a_{M-1}(\lambda_M)\,d_{M-1} = \dfrac{\psi_0}{2\pi}\lambda_M \end{array}}$$

10. Achromatic phase shift device for introducing a wavelength independent optical phase shift in a first optical beam during operation, comprising at least one dispersive element,

the at least one dispersive element comprising k element pairs (55_k), k being an integer between 1 and M, each element pair being formed by respective first refractive means (2_k) and second refractive means (4_k),

the first refractive means (2_k) having a first refractive means input plane (6) for receiving the first optical beam (40) and a first refractive means output plane (8), the first refractive means input plane (6) and the first refractive means output plane (8) being at a predetermined angle β_k to each other, $0 < \beta_k < \pi/2$,

the second refractive means (4_k) having a second refractive means input plane (10) and a second refractive means output plane (12), said second refractive means input plane (10) being positioned equidistant to the first refractive means output plane (8) and the second refractive means output plane (12) being positioned parallel to the first refractive means input plane (6),

characterised in that

~~12. Device according to one of the claims 1 through 10, characterised in that~~

the device introduces a predetermined phase shift ψ_0 between the first optical beam (40) and a second optical beam (41), the second optical beam (41) running substantially

parallel to the first optical beam (40) over an optical path length w_0, a first optical axis (50) being defined from a device input surface (51) to a device output surface (52), the first refractive means (2_k) having a first distance d_k' along the first optical axis (50) and the second refractive means having a second distance d_k'' along the first optical axis (50), the first optical beam (40) being at an angle Θ_k with the first optical axis (50) and a modified refractive index a_k being defined as $a_k = n_k \cos \Theta_k$,

in which the sum d_k of the first and second distance of the first and second refractive means (2_k, 4_k), respectively, and the required optical path w_0 are determined by requiring constant terms and terms with $\lambda^2, \lambda^3, \ldots, \lambda^M$ to become zero and the term with λ to become equal to $\psi_0/2\pi$ in the equation for the introduced optical path length difference $w_d(\lambda)$ according to

A1

$$w_d(\lambda) = -w_0 + \sum_{k=0}^{M-1} \{a_{k0} + a_{k1}(\lambda - \lambda_0) + a_{k2}(\lambda - \lambda_0)^2 \cdots\cdots\cdots\} d_k$$

in which $a_{k0}, a_{k2}, \ldots$ = series expansion coefficients of the modified refractive index a_k, according to

$$a_k = a_{k0} + a_{k1}(\lambda - \lambda_0) + a_{k2}(\lambda - \lambda_0)^2 \cdots\cdots\cdots$$

in which λ is a wavelength of the optical beam (40) and λ_0 is a central wavelength of a predetermined spectral band.

Sub a3

11~~3~~. Interferometer having a first input plane and a second input plane for receiving at least a first and a second optical beam and an interference plane for letting the at least first and second optical beam interfere, a first optical path being formed from the first input plane to the interference plane and a second optical path being formed from the second input plane to the interference plane,

comprising optical path delay means for introducing an optical path difference between the first optical path and the second optical path, **characterised in that** the interferometer further comprises at least one achromatic phase shift device according to one of the claims 1 through 10~~2~~, positioned in at least one of the first optical path and the second optical path.

12~~4~~. Interferometer according to claim 11~~3~~, **characterised in that** an achromatic phase shift device is positioned in each optical path.

Sub a4

1<u>3</u>~~5~~. Interferometer according to claim 1<u>1</u>~~3~~ or 1<u>2</u>~~4~~, **characterised in that** the interferometer comprises main control means for maintaining the phase shift (ψ_0) between the at least first and second beam at a predetermined value, the main control means being connected to the optical path delay means (26,27), and the first control means.

A1 Cond

1<u>4</u>~~6~~. Interferometer according to claim 13 ~~145~~, **characterised in that** the predetermined value is equal to π.

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